

Dynamical ordering in the c-axis in 3D driven vortex lattices

Alejandro B. Kolton, Daniel Domínguez ^a and Niels Grønbech-Jensen ^{b c}

^aCentro Atómico Bariloche,
8400 S. C. de Bariloche, Rio Negro, Argentina

^bDepartment of Applied Science, University of California,
Davis, California 95616, USA

^cNERSC, Lawrence Berkeley National Laboratory,
Berkeley, California 94720, USA

We present molecular dynamics simulations of driven vortices in layered superconductors in the presence of an external homogeneous force and point disorder. We use a model introduced by J.R.Clem for describing 3D vortex lines as stacks of 2D pancake vortices where only magnetic interactions are considered and the Josephson interlayer coupling is neglected. We numerically evaluate the long-range magnetic interaction between pancake vortices exactly. We analyze the vortex correlation along the field direction on (c-axis). We find that above the critical current, in the “plastic flow” regime, pancakes are completely uncorrelated in the c-direction. When increasing the current, there is an onset of correlation along the c-axis at the transition from plastic flow to a moving smectic phase. This transition coincides with the peak in the differential resistance.

1. INTRODUCTION

The prediction [1] of a *dynamical phase transition* upon increasing drive, from a fluidlike plastic flow regime [2] to a coherently moving solid [1] in a moving vortex lattice has motivated many recent theoretical [3], experimental [4–6], and simulation work [7–13]. In a previous work we have studied the dynamical regimes in the velocity-force curve (voltage-current) in 2D thin films [10] and found two dynamical phase transitions above the critical force. The first transition, from a plastic flow regime to a smectic flow regime, is characterized by the simultaneous occurrence of a peak in differential resistance, isotropic low frequency voltage noise and maximum transverse diffusion. The second transition, from a smectic flow regime to a frozen transverse solid, is a freezing transition in the transverse direction where transverse diffusion vanishes abruptly and the Hall noise drops many orders of magnitude. In other 2D simulations the peak in differential resistance was found to coincide with the onset of orientational order [8] and a maximum number of defects [9]. Exper-

imentally, the position of this peak was taken by Hellerqvist *et al.* [5] as an indication of a dynamical phase transition. In this paper we show that in driven 3D layered superconductors, the peak in differential resistance also coincides with the onset of correlation along the c-axis.

2. MODEL

Simulations of vortices in 3D layered superconductors have been done previously using time-dependent Ginzburg–Landau–Lawrence–Doniach equations (two layers), [12], the 3D XY model [13] and Langevin dynamics of interacting particles [14,15]. Here we study the motion of pancakes vortices in a layered superconductor with disorder, with an applied magnetic field in the c-direction and with an external homogeneous current in the layers (ab-planes). We use a model introduced by J.R. Clem for a layered superconductor with vortices in the limit of zero Josephson-coupling between layers [16]. We simulate a stack of equally spaced superconducting layers with interlayer periodicity s , each layer containing the

same number of pancake vortices. The equation of motion for a pancake located in position $\mathbf{R}_i = (\mathbf{r}_i, z_i) = (x_i, y_i, n_i s)$ (with z-axis in c-direction) is:

$$\eta \frac{d\mathbf{r}_i}{dt} = \sum_{j \neq i} \mathbf{F}_v(\rho_{ij}, z_{ij}) + \sum_p \mathbf{F}_p(\rho_{ip}) + \mathbf{F}, \quad (1)$$

where $\rho_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$ and $z_{ij} = |z_i - z_j|$ are the in-plane and inter-plane distance between pancakes i, j , $r_{ip} = |\mathbf{r}_i - \mathbf{r}_p|$ is the in-plane distance between the vortex i and a pinning site at $\mathbf{R}_p = (\mathbf{r}_p, z_i)$ (pancakes interact only with pinning centers within the same layer), η is the Bardeen-Stephen friction, and $\mathbf{F} = \frac{\Phi_0}{c} \mathbf{J} \times \mathbf{z}$ is the driving force due to an applied in-plane current density \mathbf{J} . We consider a random uniform distribution of attractive pinning centers in each layer with $\mathbf{F}_p = -A_p e^{-(r/r_p)^2} \mathbf{r}/r_p^2$, where r_p is the pinning range. The magnetic interaction between pancakes $\mathbf{F}_v(\rho, z) = F_\rho(\rho, z) \hat{r}$ is given by:

$$F_\rho(\rho, 0) = (\phi_0^2/4\pi^2\Lambda\rho)[1 - (\lambda_{\parallel}/\Lambda)(1 - e^{-\rho/\lambda_{\parallel}})](2)$$

$$F_\rho(\rho, z) = (\phi_0^2\lambda_{\parallel}/4\pi^2\Lambda^2\rho)[e^{-z/\lambda_{\parallel}} - e^{-R/\lambda_{\parallel}}]. \quad (3)$$

Here, $R = \sqrt{z^2 + \rho^2}$, λ_{\parallel} is the penetration length parallel to the layers, and $\Lambda = 2\lambda_{\parallel}^2/s$ is the 2D thin-film screening length. A analogous model to Eqs. (2-3) was used in [14]. We normalize length scales by λ_{\parallel} , energy scales by $A_v = \phi_0^2/4\pi^2\Lambda$, and time is normalized by $\tau = \eta\lambda_{\parallel}^2/A_v$. We consider N_v pancake vortices and N_p pinning centers per layer in N_l rectangular layers of size $L_x \times L_y$, and the normalized vortex density is $n_v = N_v \lambda_{\parallel}^2/L_x L_y = B \lambda_{\parallel}^2/\Phi_0$. Moving pancake vortices induce a total electric field $\mathbf{E} = \frac{B}{c} \mathbf{v} \times \mathbf{z}$, with $\mathbf{v} = \frac{1}{N_v N_l} \sum_i \mathbf{v}_i$. We study the dynamical regimes in the velocity-force curve at $T = 0$, solving Eq. (1) for increasing values of $\mathbf{F} = F\mathbf{y}$. We consider a constant vortex density $n_v = 0.1$ in $N_l = 5$ layers with $L_x/L_y = \sqrt{3}/2$, $s = 0.01$, and $N_v = 36$ pancake vortices per layer. We take a pinning range of $r_p = 0.2$, pinning strength of $A_p/A_v = 0.2$, with a density of pinning centers $n_p = 0.65$ on each layer. We use periodic boundary conditions in all directions and the periodic long-range in-plane interaction is dealt with exactly using an exact and fast converging sum

[17]. The equations are integrated with a time step of $\Delta t = 0.01\tau$ and averages are evaluated in 16384 integration steps after 2000 iterations for equilibration (when the total energy reaches a stationary value). Each simulation is started at $F = 0$ with an ordered triangular vortex lattice (perfectly correlated in c-direction) and slowly increasing the force in steps of $\Delta F = 0.1$ up to values as high as $F = 8$.

3. RESULTS

We start by looking at the vortex trajectories in the steady state phases. In Figure 1(a-b) we show a top view snapshot of the instantaneous pancake configuration for two typical values of F . In Figure 2(a-b) we show the vortex trajectories $\{\mathbf{R}_i(t)\}$ for the same two typical values of F by plotting all the positions of the pancakes in all the layers for all the time iteration steps. In Fig. 3(a) we plot the average vortex velocity $V = \langle V_y(t) \rangle = \langle \frac{1}{N_v} \sum_i \frac{dy_i}{dt} \rangle$, in the direction of the force as a function of F and its corresponding derivative dV/dF . We also study the pair distribution function:

$$g(\rho, n) = \frac{1}{N_p N_l} \langle \sum_{i < j} \delta(\rho - \rho_{ij}) \delta(ns - z_{ij}) \rangle. \quad (4)$$

In Fig. 3(b) we plot a correlation parameter along c-axis defined as:

$$C_z^n = \lim_{\rho \rightarrow 0} g(\rho, n), \quad (5)$$

as a function of F for $n = 1, 2$. Below a critical force, $F_c \approx 0.4$, all the pancakes are pinned and there is no motion. At the characteristic force, $F_p \approx 0.8$, we observe a peak in the differential resistance. At F_c pancake vortices start to move in a few channels, as was also seen in 2D vortex simulations [2]. A typical situation is shown in Fig. 2(a). In this plastic flow regime we observe that the motion is completely uncorrelated along c-direction, with $C_z^n \approx 0$ for $F_c < F < F_p$ as shown in Fig. 3(b). In Fig. 1(a) and 2(a) we see that this situation corresponds to a disordered configuration of pancakes and to an uncorrelated structure of plastic channels along c-axis. At F_p there is an onset of correlation along the c-axis and pancakes

vortices start to align forming well defined stacks or vortex lines. This onset of c-axis correlation corresponds to the transition from plastic flow to a moving smectic phase (a complete discussion of the translational as well as temporal order will be discussed elsewhere [18]). For $F > F_p$ we observe that the structure of smectic channels is very correlated in the c-direction.

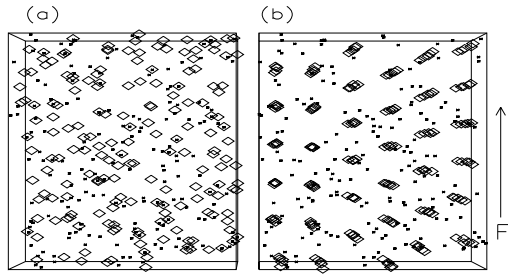


Figure 1. Pancake configuration (top view of the layers) for two typical values of F , (a) $F_c < F = 0.7 < F_p$, (b) $F_p < F = 2.5$. Diamonds (\diamond) represent pancake vortices and asterisks ($*$) represent pinning centers.

4. DISCUSSION

In a system with $N_l = 5$ layers we have found that there is a clear onset of c-axis correlation with increasing driving force, where the pancake vortices start to align forming well defined stacks moving in smectic flow channels. Below this transition, in the plastic flow regime, these stacks of pancakes are unstable. Also, in [12] an enhancement of c-axis correlations with increasing drive was observed in a bilayered system.

We have further found [18] that the in-plane properties are in well correspondence with the ones obtained in 2D thin films simulations [10]. A

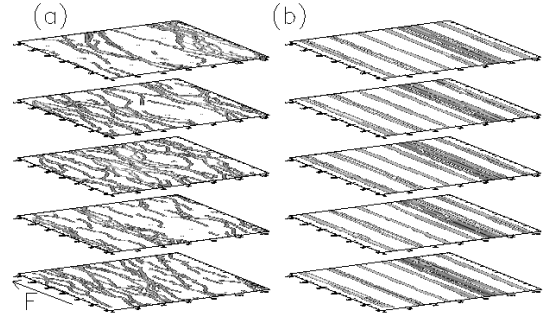


Figure 2. Pancake trajectories for two typical values of F , (a) $F_c < F = 0.7 < F_p$, (b) $F_p < F = 2.5$, obtained plotting all the positions of the pancakes for all time iteration steps.

better understanding of the effects of c-axis correlations in pancake motion on each layer can be obtained by studying translational and temporal order in larger systems, through the analysis of the structure factor, voltage noise, and in-plane [11] as well as *inter-plane* velocity-velocity correlation functions [18].

In conclusion we have analyzed the vortex correlation along the field direction (c-axis) in the velocity-force characteristics at $T = 0$ and found that above the critical current there is an onset of c-axis correlation in the transition between a plastic flow regime to a smectic flow regime. This transition coincides with the peak in the differential resistance. Experimentally, this effect could be studied with measurements of c-axis resistivity as a function of an applied current parallel to the layers [19].

We acknowledge discussions with L.N. Bulaevskii, P.S. Cornaglia, F. de la Cruz, Y. Fasano, M. Menghini and C.J. Olson. This work has been supported by a grant from ANPCYT (Argentina), Proy. 03-00000-01034. D.D. and A.B.K. acknowledge support from Fundación An-

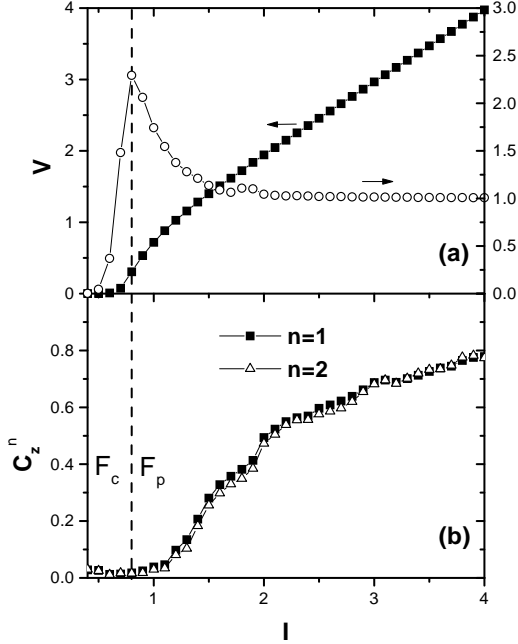


Figure 3. (a) Velocity-force curve (voltage-current characteristics), left scale, black points, dV/dF (differential-resistance), right scale, white points. (b) Correlation parameter along c-axis C_z^n for $n = 1, 2$.

torchas (Proy. A-13532/1-96), Conicet, CNEA and FOMEC (Argentina). This work was also supported by the Director, Office of Advanced Scientific Computing Research, Division of Mathematical, Information, and Computational Sciences of the U.S. Department of Energy under contract number DE-AC03-76SF00098.

REFERENCES

1. A. E. Koshelev and V. M. Vinokur, Phys. Rev. Lett. **73**, 3580 (1994).
2. H. J. Jensen *et al.*, Phys. Rev. Lett. **60**, 1676 (1988); A.-C. Shi and A. J. Berlinsky, Phys. Rev. Lett. **67**, 1926 (1991).
3. T. Giamarchi and P. Le Doussal, Phys. Rev. Lett. **76**, 3408 (1996); P. Le Doussal and T. Giamarchi, Phys. Rev. B **57**, 11356 (1998); L. Balents, M. C. Marchetti and L. Radzihovsky, Phys. Rev. B **57**, 7705 (1998); S. Scheidl and V. M. Vinokur, Phys. Rev. E **57**, 2574 (1998); Phys. Rev. B **57**, 13800 (1998).
4. M. J. Higgins and S. Bhattacharya, Physica C **257**, 232 (1996).
5. M. C. Hellerqvist *et al.*, Phys. Rev. Lett. **76**, 4022 (1996).
6. F. Pardo *et al.*, Nature (London) **396**, 348 (1998).
7. K. Moon, R. T. Scalettar and G. Zimányi, Phys. Rev. Lett. **77**, 2778 (1996); S. Spencer and H. J. Jensen, Phys. Rev. B **55**, 8473 (1997).
8. S. Ryu *et al.*, Phys. Rev. Lett. **77**, 5114 (1996).
9. C. J. Olson, C. Reichhardt and F. Nori, Phys. Rev. Lett. **81**, 3757 (1998).
10. A. B. Kolton, D. Domínguez, N. Grønbech-Jensen, Phys. Rev. Lett. **83**, 3061 (1999).
11. D. Domínguez, Phys. Rev. Lett. **82**, 181 (1999).
12. I. Aranson, A. Koshelev and V. Vinokur, Phys. Rev. B **56**, 5136 (1997).
13. D. Domínguez, N. Grønbech-Jensen and A.R. Bishop, Phys. Rev. Lett. **78**, 2644 (1997).
14. D. Reefman, H. B. Brom, Physica C **213**, 229 (1993).
15. S. Ryu, D. Stroud, Phys. Rev. B, **54**, 1320 (1996); N. K. Wilkin, H. J. Jensen, Phys. Rev. Lett. **21**, 4254 (1997); A. van Otterlo, R. T. Scalettar, G. T. Zimányi, Phys. Rev. Lett. **81**, 1497 (1998); C. J. Olson, R. T. Scalettar, G. T. Zimányi, cond-mat/9909454.
16. J. R. Clem, Phys. Rev. B. **43**, 7837 (1990).
17. N. Grønbech-Jensen, Int. J. Mod. Phys. C **7**, 873 (1996); Comp. Phys. Comm. **119**, 115 (1999).
18. A. B. Kolton, D. Domínguez, N. Grønbech-Jensen, to be published.
19. M. Menghini (private communication).